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II.

CONSTITUTION OF THE INTERIOR OF THE EARTH AS INDICATED BY SEISMOLOGICAL INVESTIGATIONS.

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(*Read April 24, 1915.*)

In 1883 Milne predicted that earthquake disturbances would be registered by seismographs at great distances from their origin, a prediction first verified when the earthquake of April 18, 1889, whose origin lay off the coast of Japan, affected the horizontal pendulum which von Rebeur-Paschwitz had set up at Potsdam to study the attraction of the moon. Milne was so convinced of the correctness of his idea and of the importance of the results to be obtained that in 1893 he established an observatory on the Isle of Wight to record earthquakes from distant regions; and he also succeeded in having instruments of similar model set up at observatories very widely scattered in various parts of the world.

Wertheim in 1851 showed that a disturbance in the interior of an elastic solid would break up into two groups of waves, longitudinal and transversal, which would be propagated at different rates, and as their velocities are so great that they cannot be separated from each other in the laboratory he suggested with rare insight that their separation might first be noticed in connection with the propagation of earthquake disturbances.[1] A few years later Lord Rayleigh showed that a third kind of wave could be propagated along the surface of the earth.[2] Seismologists naturally looked for indications of these three groups of waves in their seismograms, but it was not until 1900 that Oldham succeeded in showing definitely that the seismograms of a number of Milne instruments gave clear evidence of the existence of three groups of waves. Oldham also published a diagram, which was an extension of Seebach's so-called "hodograph," showing the relation between the time of transmission of each group and the distance from the earthquake origin, measured along the surface of the earth. Milne soon improved these curves by adding observations of a large number of recorded shocks.[3] The general forms of the transmission curves are shown in the diagram. It will be seen that the curves of the first and second "preliminary tremors," as Milne called the first two groups of waves, are curved, indicating that the velocity of transmission increases with the distance from the origin; a conclusion which had already been drawn from earlier, but less accurate, observations. Milne attempted to explain this by assuming that the path of the seismic disturbance lay along the chord and not along the earth's surface; this practically shortens the distance to the observing stations, and if the curves are plotted, with distances

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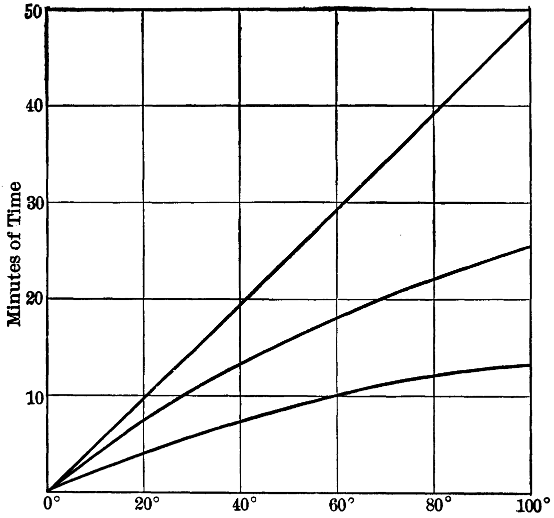
[1] "Sur la propagation du movement dans les corps solides et liquides," *Ann. de Chimie et Phys.*, 1851, Vol. XXI., p. 19.

[2] "On Waves Propagated along the Plane Surface of an Elastic Solid," *Proc. London Math. Soc.*, 1855, Vols. XLVII., L.



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[3] Rep. of the Com. on Seismol. Investig., B. A. A. S., 1902, p. 7.

measured along the chord, the curvature is considerably diminished; but later and more accurate observations show that even under this assumption the velocity still increases with the distance. The conclusion is unavoidable that as the path of the disturbance sinks deeper into the earth the velocity increases. The interior of the earth then is not a homogeneous but a refractive medium, and the path of the disturbance cannot be straight but must be curved with the concavity turned upward. This condition had been described by A. Schmidt as early as 1888.[4] Seismologists now believe that the three groups discovered by Oldham are respectively the longitudinal, the transverse and the surface waves. The transmission curve of the latter is a straight line indicating that the waves are transmitted with uniform velocity along the surface of the earth. They have affected seismographs after having passed completely around the earth. It cannot be said that the evidence, that the first two groups are respectively longitudinal and transverse, is complete; but it is sufficient, in connection with theory, to make seismologists fairly confident that the conclusion is correct; and the passage of transverse waves through the earth to great depths is proof that, to those depths, the earth is solid; for transverse waves cannot exist in a liquid. Further, since the velocity of transmission depends on the ratio of the elasticity to the density of the medium, and since both the longitudinal and transverse waves increase in velocity with the depth below the surface, both the elasticity of volume and the elasticity of figure of the earth, not only increase, but increase more rapidly than the density as we penetrate below the surface. The earth therefore is not only rigid, but its rigidity increases towards its center; though seismological evidence does not yet prove that this characteristic extends to the very center itself.

The next step was to determine the path of the waves in the earth and their velocity at different depths; the data for these determinations were the times of arrival of the earthquake waves at various distances from the origin; these times are collected in the transmission curves. At first sight this seems an insoluble problem;

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[4] "Wellenbewegung und Erdbeben," *Jahreshefte für Vaterlands Naturkunde in Württemberg,* 1888, p. 248.

but, thanks to a remarkable mathematical theorem of Abel, it is not. It is clear that the time of arrival of an earthquake disturbance at a distant station will depend on the path followed and the velocity in different parts of the path, and if we make the reasonable assumption, which is borne out by observation, that the velocity is everywhere the same at the same depth, then it is evident, if the velocity increases continuously with the depth, that the transmission curves will be continuous without breaks, and their curvatures will nowhere make a sudden change. The mathematical solution of the problem has been obtained by Wiechert, Bateman and others, and concrete results have been obtained by Wiechert and his assistants, so that we now know the paths of the waves and their velocities with a fair degree of accuracy, at least to a considerable distance below the surface. But the questions arise: do the velocities increase continuously with the depth; and if so, how? questions which could be answered by the study of perfect transmission curves; but even imperfect curves yield some information; which, however, may be so faulty that it must be received with great caution. Milne, who has done such excellent pioneer work in seismology, was the first to propose and attempt to answer these questions.[5] He thought the transmission curve could be satisfied by supposing the earth to consist of a solid core having a radius of nineteen twentieths of the earth's radius, and surrounded by a thin shell. The core was of uniform density and elasticity, so that the velocity of propagation in it was uniform, and the paths of the rays would be straight lines. The velocity in the shell was much less than in the core. These conditions satisfied fairly well the very imperfect transmission curve of 1902, but they may be dismissed without further consideration, for such an earth could not satisfy the astronomic requirements, which exact, at the same time, the proper mean density and moment of inertia.

Benndorff in 1906 thought he found evidence of a central core of about four fifths the earth's radius, surrounded by two shells, the outer one having the same thickness as Milne's.[6] In the same year Oldham deduced from the transmission curves a central core of not more than four tenths the earth's radius in which the velocity was distinctly less than in the surrounding shell.[7] Neither of these arrangements have been shown to conform to the astronomic requirements. Oldham's conclusions are based on what he considers a distinct break in the transmission curve of the transverse waves at distances between 120° and 150° from the origin; but when we remember that fully 95 per cent. of the energy of an earthquake shock comes to the surface within the hemisphere having the origin as its pole, we see that the data for great distances must be too imperfect to yield very reliable deductions.

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[5] Rep. of the Com. on Seismol. Investigation, B. A. A. S., 1903, p. 7.

[6] "Ueber die Art der Fortpflanzungsgeschwindigheit der Erdbebenwellen in Erdinnern," *Mitt. d. Erdbeben Com. k. Akad. Wiss. in Wien,* 1905, Nos. XXIX. and XXXI.

Many years ago Roche showed that it was quite possible to determine a distribution of density in the earth which would be discontinuous at several levels, but which would still be astronomically satisfactory. Wiechert, in 1897,[8] showed that such a system might consist of a central core of radius about 4,900 km. or three fourths of the earth's radius, consisting of iron with a density of about 8.3, surrounded by a stony shell about 1,500 km. thick and with density varying from 3 to 3.4. It was natural that he should examine the transmission curves to see if they supported his ideas; and at the Hague meeting of the International Seismological Association in 1907 he announced that they did. At the Manchester meeting of the same association in 1911 he announced the existence of two shells around the central core. In 1914 Gutenberg (one of Wiechert's assistants) announced the existence of three shells.[9] In addition to ordinary times of transmission, Gutenberg also used the times of waves reflected at the earth's surface and the variations in the amplitude; it is evident that a wave which crosses the boundary of the core will experience reflection and refraction; and whichever part is later observed at the surface of the earth will have a distinctly smaller amplitude than the wave which just missed penetrating into the core. The following table shows the positions of the boundaries of the shells and of the core, and the velocities of the longitudinal waves *P* and of the transverse waves *S;* it will be noticed that it is only at the boundary of the central core that any marked sudden change in velocity occurs.

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[7] Constitution of the Interior of the Earth, *Quart. Jour. Geol. Soc.*, 1906, Vol. LXII., p. 456.

[8] "Ueber die Massenvertheilung im Innern der Erde," *Nachr. k. Gesells. Wiss. Göttingen*, 1897; *Math.-phys. Kl.*, p. 221.

[9] "Ueber Erdbebenwellen," VIIA. *Nach. k. Gesells. Wiss. Göttingen; Math.-phys. Kl.*, 1914, p. 1; references to the earlier numbers of the series are given in this paper.

	Veloc. km./sec.	
Depth, kms.	*P.*	*S.*
0	7.17	4.01
1200	11.80	6.59
1700	12.22	6.86
2450	13.29 13.15	7.32 7.20
2900	13.15 8.50	7.20 4.72
6370	11.10	6.15

The remark regarding Oldham's results applies also here, namely that it is questionable whether the observations at distances greater than 100° or 120° are sufficiently accurate to justify such definite conclusions. Gutenberg had the advantage, however, of more accurate observations than Oldham, and also of measures of amplitudes. There is no *a priori* reason why the earth might not be made up of a number of shells, but there should be satisfactory evidence for any proposed system; and it must be shown to satisfy the astronomic requirements; or, at least, not to contradict them. Gutenberg's system does not correspond with Wiechert's system of 1897. In the latter a marked change in physical properties occurs at a depth of 1,500 km.; in the former, at a depth of 2,900 km.; and in crossing into the core, the ratio of the elasticity to the density, according to Gutenberg, rapidly loses six tenths of its value. This change might be the result of a great increase in density or a great decrease in elasticity; it may be questioned whether the former is compatible with the astronomic requirements, and whether the latter is compatible with the high rigidity which we know the earth, as a whole, has. So far no answer has been given to these questions.

In 1879 George and Horace Darwin attempted to determine the rigidity of the earth by measuring the deviation of the vertical under the attraction of the moon. If the earth yielded like a fluid, its surface would always remain at right angles to the vertical, and a pendulum would remain relatively stationary for all positions of the moon; if the earth were absolutely rigid, the moon's attraction would deflect the pendulum an extremely small amount, but an amount capable of being measured. The Darwins did not obtain definite results because the disturbances of their pendulum were greater than the deflections they attempted to determine.

A little later von Rebeur-Paschwitz attacked the same problem with better success, using a horizontal pendulum.

Hecker, in Potsdam, and Orloff, in Dorpat, have repeated von Rebeur-Paschwitz's experiment; and both found values for the average rigidity of the earth comparable with that of steel. But, what was most remarkable and what is still unexplained, the rigidity was apparently greater in an east-west than in a north-south direction. Orloff, experimenting at a greater distance from the ocean, found a smaller difference than Hecker did, and it has been suggested that the tides of the ocean are the cause of the difference. The International Seismological Association, at its Manchester meeting in 1911, made plans to repeat the experiments in Paris, in central Canada, in the middle of Southern Africa and in the middle of Russia; but no reports have yet come from these stations.

In the autumn of 1913, Michelson attacked the same problem by a new method, which seems capable of yielding more accurate results than the horizontal pendulum. He measured the deflection of the vertical under the influence of the moon by what was practically a water level 500 feet long, sunk six feet in the earth.[10] Michelson's results for the E-W rigidity do not differ greatly from those of Orloff; but his N-S rigidity is somewhat less than Orloff's. Michelson's experiments also show that the viscosity of the earth must be as great as that of steel. These experiments are of great interest; they should be repeated at various places, and especially at places symmetrically situated with respect to the great oceans, and on mid-oceanic islands, in order to determine how far they are affected by the oceanic tides.

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[10] "Preliminary Results of Measurements of the Rigidity of the Earth," *The Astrophysical Journal,* 1914, Vol. XXXIX., p. 97.

We can say in conclusion, that the transmission of transverse earthquake waves shows that the earth is solid, at least to a great depth below the surface; and that experiments on the deflection of the vertical show that it is quite as rigid and as viscous as steel. There are still difficulties in the interpretation of the observations, but their elucidation cannot alter the general character of the conclusions.